INFRASOUND SENSOR MODELS AND EVALUATION

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Sponsored by U.S. Department of Energy
Office of Nonproliferation and National Security
Office of Research and Development
National Nuclear Security Administration

Contract No. DE-AC04-94AL85000

ABSTRACT

Sandia National Laboratories has continued to evaluate the performance of infrasound sensors that are candidates for use by the International Monitoring System (IMS) for the Comprehensive Nuclear-Test-Ban Treaty Organization. The performance criteria against which these sensors are assessed are specified in *Operational Manual for Infrasound Monitoring and the International Exchange of Infrasound Data* (CTBT/WGB/TL-11/4/Rev8/Appendix I[1]).

This presentation includes the results of efforts concerning two of these sensors:
- Chaparral Physics Model 5
- CEA MB2000

Sandia is working with Chaparral Physics in order to improve the capability of the Model 5 (a prototype sensor) to be calibrated and evaluated. With the assistance of the Scripps Institution of Oceanography, Sandia is also conducting tests to evaluate the performance of the CEA MB2000. Sensor models based on theoretical transfer functions and manufacturer specifications for these two devices have been developed. This presentation will feature the results of coherence-based data analysis of signals from a “huddle” test, utilizing several sensors of both types, in order to verify the sensor performance.

Key Words: infrasound, sensor, evaluation, instrumentation

OBJECTIVE

The infrasound sensor evaluation task has the following objectives:
- Define characteristics of the Chaparral Physics Model 5 microbarograph.
- Evaluate the performance of the Chaparral 5 sensor with respect to IMS requirements using the IS-59 sensors deployed on Hawaii.
- Perform side-by-side testing of both CEA MB2000 and Chaparral Physics Model 5 infrasound sensors to compare relative sensor responses.

RESEARCH ACCOMPLISHED

Chaparral Physics Model 5 Microbarograph

Characteristics
- Smaller backing volume and leak than the Chaparral 4 to minimize effects from regional barometric pressure changes.
- Sensitivity of 100 mV/Pa (10 mV/(Bar) to maximize dynamic range and improve matching to 24-bit digitizers.
- Wide-range DC power supply (9-18 Vdc) to allow the sensor to operate directly from solar panels or unregulated power.
- Diagnostic capability to enable measurement of sensor self-noise and electronics gain.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **Infrasound Sensor Models And Evaluation**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Sandia National Laboratories,P.O. Box 5800,Albuquerque,NM,87123**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the 22nd Annual DoD/DOE Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) held in New Orleans, Louisiana on September 13-15, 2000, U.S. Government or Federal Rights.

14. ABSTRACT
See Report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Sensor Performance and IMS Requirements:

A comparison of Key Infrasound IMS requirements (Table 1) to Chaparral 5 sensor performance was performed.

Characteristics	Minimum Requirements
Sensor Noise	≤18 dB below minimum acoustic noise[1]
Calibration	≤5 % in absolute amplitude[2]
Dynamic Range	≥108 dB

[1] Minimum noise level at 1 Hz: ~ 5mPa(RMS√Hz)
[2] Periodicity: once per year (minimum)

Table 1- Key Infrasound Requirements (CTBT/WGB/TL-11/4/Rev8/Appendix I[1])

Sensor Noise Requirement: ≤18 dB below minimum acoustic noise of 5mPa(RMS√Hz) at 1 Hz

The specification of 18 dB below 5 mPa(RMS√Hz) at 1 Hz is 0.63 mPa(RMS√Hz) is equivalent to -64 dB relative to 1 Pa^2/Hz.

The Chaparral 5 sensor has the capability to substitute a fixed reference capacitor in place of the microphone element using an internal relay. In this mode, sensor self-noise can be accurately measured, even in a field environment. This technique was used in measuring sensor self-noise of the Chaparral 5 sensors installed in IS-59, Hawaii. A PDS of the IS-59 sensor noise with respect to IS-59 background is shown in Figure 1.

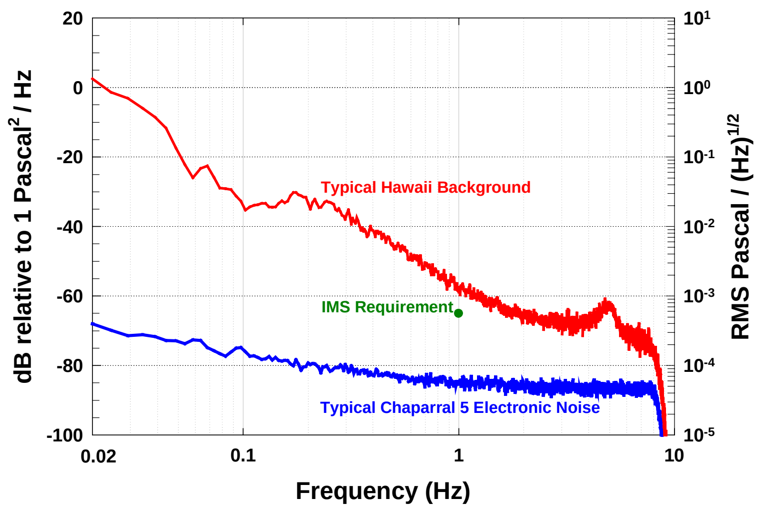

Figure 1 - Sensor Noise – IS-59 Chaparral 5 Sensors

Calibration Requirement: ≤5 % in absolute amplitude

Sensor Pressure Calibration

For a differential sensor, 5% absolute amplitude calibration is difficult to perform, especially in a field environment. Static pressure calibrations (typical 100 hPa (mBar)) such as those used on absolute barometric sensors (CEA MB2000) are not useable with differential ac-coupled sensors such as the Chaparral 5. A pressure source capable of generating small, accurate, sinusoidal signals is difficult to build, calibrate and operate. Signals are affected by ambient pressure, temperature and local atmospheric pressure changes. A process to perform 5% absolute calibration of a Chaparral 5 in a lab environment is being developed jointly by Sandia and Los Alamos National Laboratories.

The calibration solution for the Chaparral 5 is to calibrate a reference Chaparral 5 in the lab and use it as a

Secondary Standard to calibrate the production sensors. Calibration signals using piston-phone generated sinusoids provide a common stimulus to both reference and production sensors. This technique, as shown in Figure 2, was used in calibrating the Chaparral 5 sensors for installation in IS-59, Hawaii.

Figure 2 – Reference Sensor (left) and Five IS-59 Acoustically Paralleled Chaparral 5 Production Sensors

Sine-fit calculations provided a relative amplitude measurement from the reference sensor. Unfortunately, the reference sensor was not calibrated to <5%. The IS-59 sensors will have to be re-calibrated when this technique is perfected. Sensitivity of the IS-59 sensors relative to the reference sensor is shown in Table 2.

C5 Sensor Serial Number	C5_1272 Reference	C5_1322	C5_1323	C5_1324	C5_1325	C5_1326
Sensitivity Using Sinusoids	100mV/Pa	97.8mV/Pa	99.3mV/Pa	96.9mV/Pa	99.0mV/Pa	97.2mV/Pa

Table 2 – Sensitivity of IS-59 Chaparral 5 Sensors Using a Reference Sensor

Sensor Electronics Calibration

In the Chaparral 5 sensor, an electronics module provides a mechanism for converting pressure changes on the microphone element to electrical signals. The electronics module provides filtering to control the bandwidth of the sensor and amplification to set the sensitivity of these signals. A spike (similar to a step-calibration) circuit provides an indication of sensor electronics bandwidth and amplifier gain. Performing a spike calibration on a regular basis can detect changes in the electronics module performance over time and allow a form of sensor state-of-health. The amplitude of this spike is set in the Chaparral 5 to the equivalent signal of 10 Pascal. The spike can be performed with either the microphone element or a fixed reference capacitor substituted in the circuit. A change in the step-calibration with the microphone element in the circuit can indicate a defect in the microphone element. A change in the step-calibration with the fixed reference capacitor in the circuit can indicate gain or filter changes.

Dynamic Range Requirement: ≥108 dB

The Dynamic Range of a sensor usually refers to the ratio of some maximum output value to some minimum output value, usually RMS noise. For microbarograph dynamic range, Sandia uses the ratio of the peak value of the maximum sensor output to the RMS value of the sensor self-noise in a two-octave passband centered at 1 Hz (0.5 - 2 Hz). The dynamic range is measured at 1 Hz because the sensor noise limit is specified at 1 Hz. The IS-59 Chaparral 5 sensors dynamic range values are shown in Table 3.

Chaparral 5 S/N	RMS of Noise (0.5 to 2 Hz)	Dynamic Range (Peak/RMS)
1322	10.6 µv	119.5 dB
1324	7.0 µv	123.1 dB
1325	14.4 µv	116.8 dB
1326	8.1 µv	121.8 dB
1323 (spare)	3.5 µv	129.1 dB

Table 3 - IS-59 Chaparral 5 Dynamic Range

Sensor Response

The response of the Chaparral 5 is controlled by two features. An acoustical high-pass filter, determined by the combination of backing volume and leak-tube, passes the signals of interest and attenuates low-frequency barometric pressure changes. The time constant of the leak/volume is given by the expression $K=rv/\gamma P_a$ [3]. For the Chaparral 5, K= 13.3 for sea level; this is the equivalent to an electronic RC filter.

An electrical high-pass filter adds additional filtering to reduce the effect of unwanted low frequencies. For the IS-59 sensors, two pole/zeroes are contributed by the sensor electronics. One pole/zero is set by the amplifier board to a nominal RC value of 23.1; this is a nominal value as R is a function of amplifier gain and is not easily measured. A second pole/zero is set by the electronics de-coupling/output capacitor/resistor to a RC value of 110; this value assumes that the digitizer connected to the sensor has an input impedance of greater than 1 meg ohms. Low-impedance input digitizers can have significant impact on the Chaparral 5 low-frequency response.

The IS-59 and CEA MB2000 [2] sensors have an overall response (Figure 3) of:

Sensitivity: 0.100 V/Pa
Zeroes: 3 at s-plane origin
Poles: -7.52e-2, -4.33e-2, -9.1e-3

Sensitivity: 0.020 V/Pa
Zeroes: 1 at s-plane origin
Poles: -6.21e-2, -2.13e+2, -2.152e+2, -2.52e+2

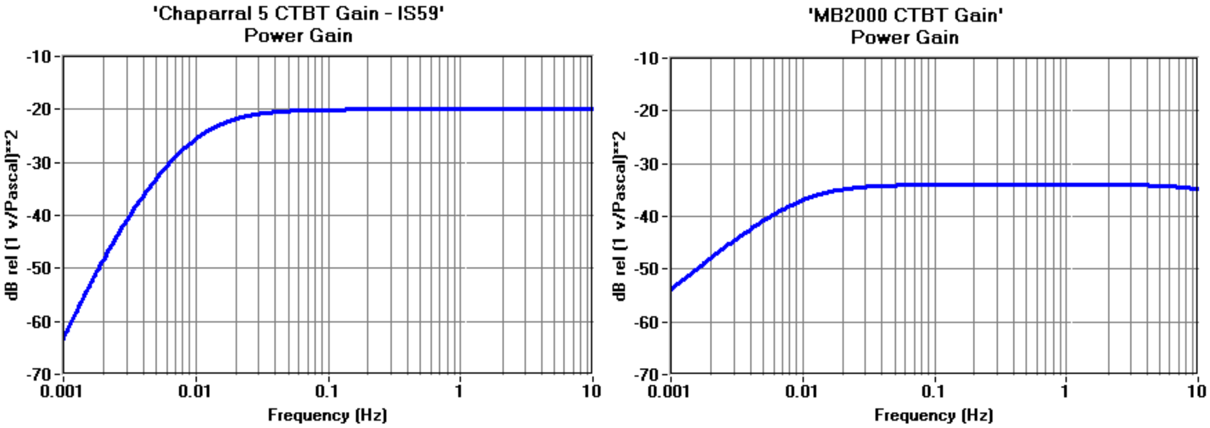

Figure 3 – IS-59 Chaparral 5 Sensor Power Gain and CEA CTBT MB2000 Power Gain

Side-by-side Comparison of CEA MB2000 and Chaparral Model 5 Sensors

A series of tests was performed at the Sandia Facility for Acceptance, Calibration and Testing (FACT) Site to compare the performance of the CEA MB2000 and Chaparral 5 sensors. Three MB2000 sensors were provided by University California San Diego/Scripps Institute of Oceanography and three Chaparral 5 sensors were provided by Southern Methodist University. The MB2000 sensors were set to a sensitivity of 20 mV/Pa. [2]; the Chaparral 5 sensors were set to a sensitivity of 400 mV/Pa. The six sensors were acoustically paralleled and connected to four porous hoses (Figure 4). Sensors were connected to a Quanterra Q4128 data acquisition system. Data were acquired over a one-week period.

Figure 4 – MB2000 and Chaparral 5 Comparison Test at Sandia FACT Site

Side-by-side coherence analysis indicated a coherence of >0.99 between the MB2000 sensors (Figure 5). The Chaparral 5 sensors showed coherence of approx. 0.8 – 0.9 between sensors (Figure 6). Coherence between the MB2000 and the Chaparral 5 sensors indicated >0.95 coherence above 0.2 Hz and <0.1 coherence below 0.1 Hz (Figure 7). A review of the data showed a diurnal cycle for coherence; it appears that the Chaparral 5 sensors are temperature and/or wind sensitive. This sensitivity appears to affect low-frequency signals (<0.2 Hz) the most.

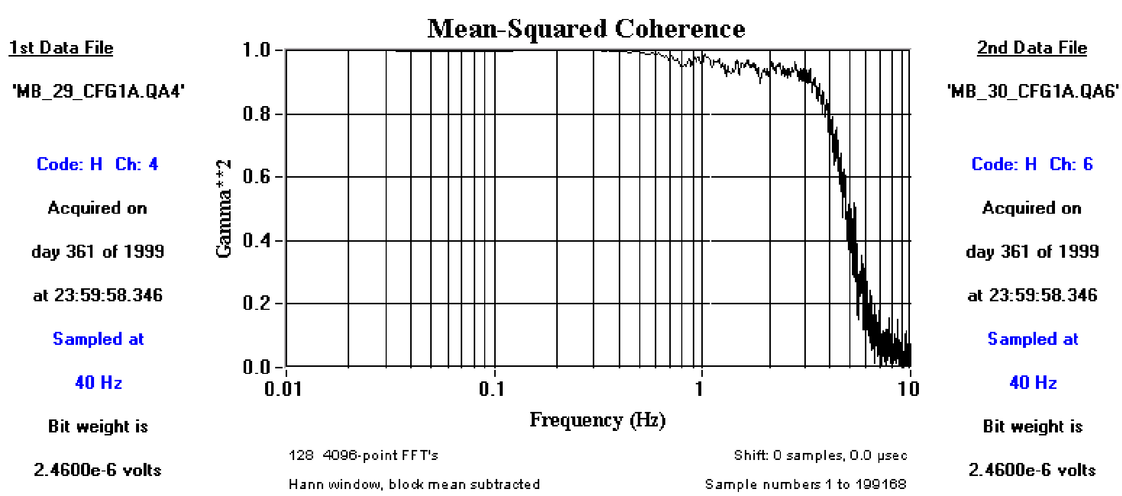

Figure 5 – Coherence Between MB2000 Sensors

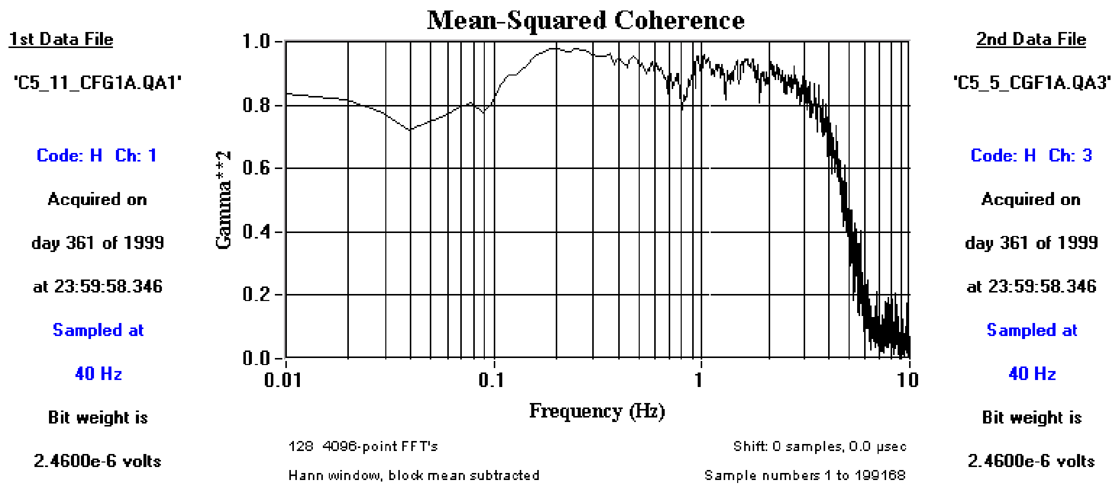

Figure 6 – Coherence Between Chaparral 5 Sensors

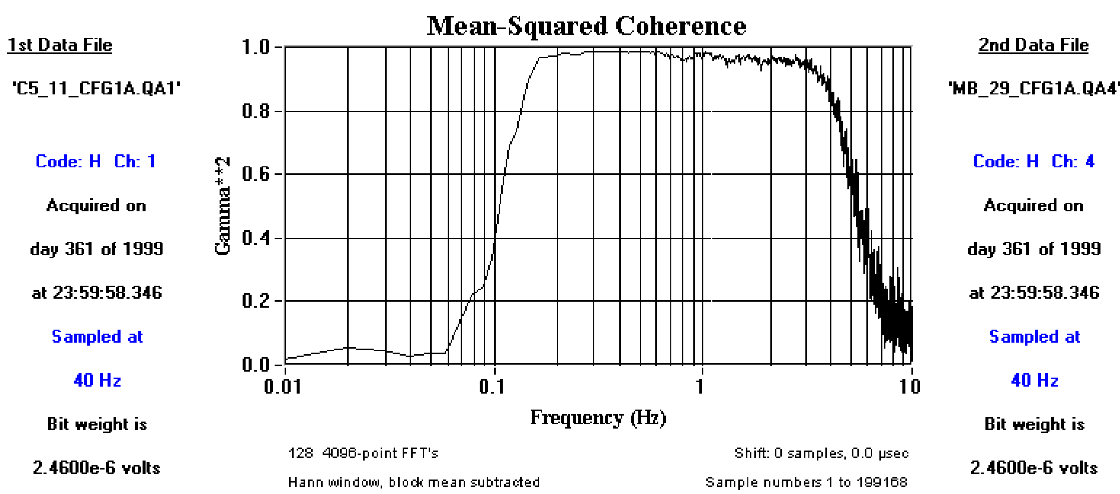

Figure 7 – Coherence Between Chaparral 5 and MB2000 Sensors

To minimize temperature effects, the Chaparral 5 sensors were packed in sand to provide thermal mass and isolate the sensors from wind (Figure 8). Data were acquired over a one-week period.

Figure 8 – MB2000 and Chaparral 5 Comparison Test at Sandia FACT Site

Side-by-side coherence analysis indicated a coherence of >0.99 between the MB2000 sensors (Figure 9). The Chaparral 5 sensors showed coherence of >0.98 between sensors (Figure 10). Coherence between the MB2000 and the Chaparral 5 sensors indicated >0.98 coherence above 0.02 Hz (Figure 11). Stabilizing the Chaparral 5 temperature and isolating the sensor from the wind corrected sensor variation. Since most applications require the sensors to be located in a buried vault, this sensitivity will not impact IMS performance. If this sensor is used for site surveys, care must be taken to insulate the sensor.

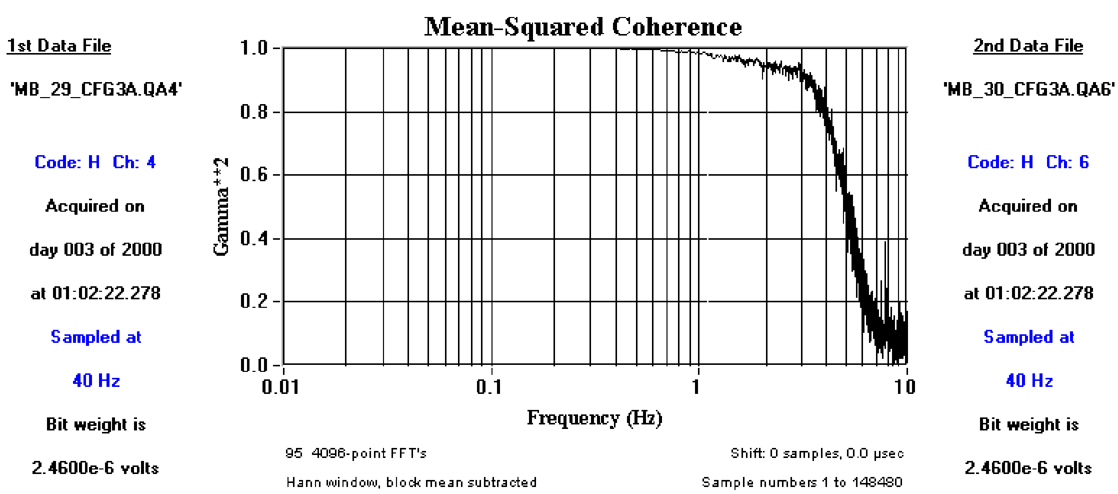

Figure 9 – Coherence Between MB2000 Sensors

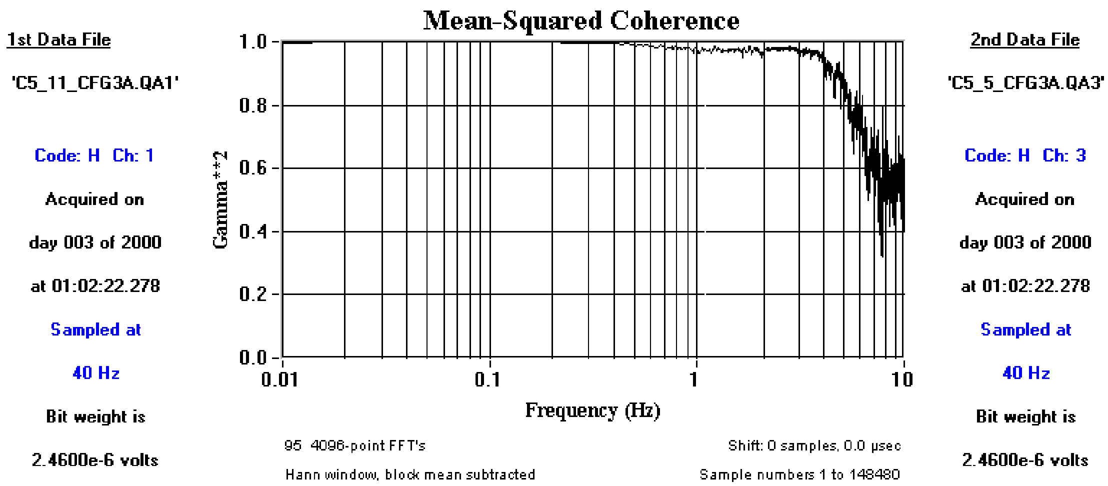

Figure 10 – Coherence Between Chaparral 5 Sensors

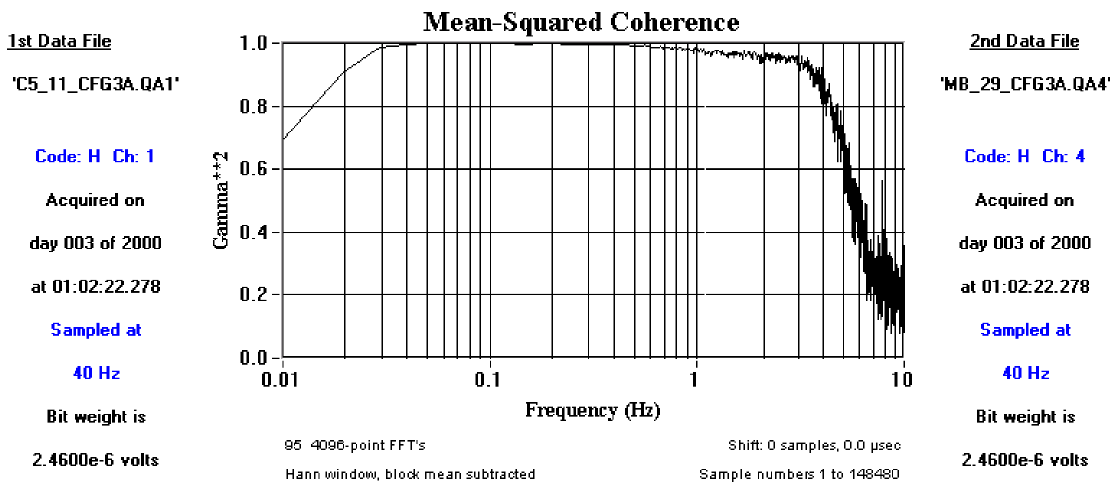

Figure 11 – Coherence Between Chaparral 5 and MB2000 Sensors

Side-by-side coherence analysis between the MB2000 and Chaparral 5 sensors indicated a relative gain difference of 26 dB. This corresponded to the gain difference of X20 between the sensors. Difference in sensitivity and phase between sensors was readily observed (Figure 12). It would appear that using the acoustical background as a common signal source for paralleled calibrated reference sensor and an installed sensor is a viable calibration technique.

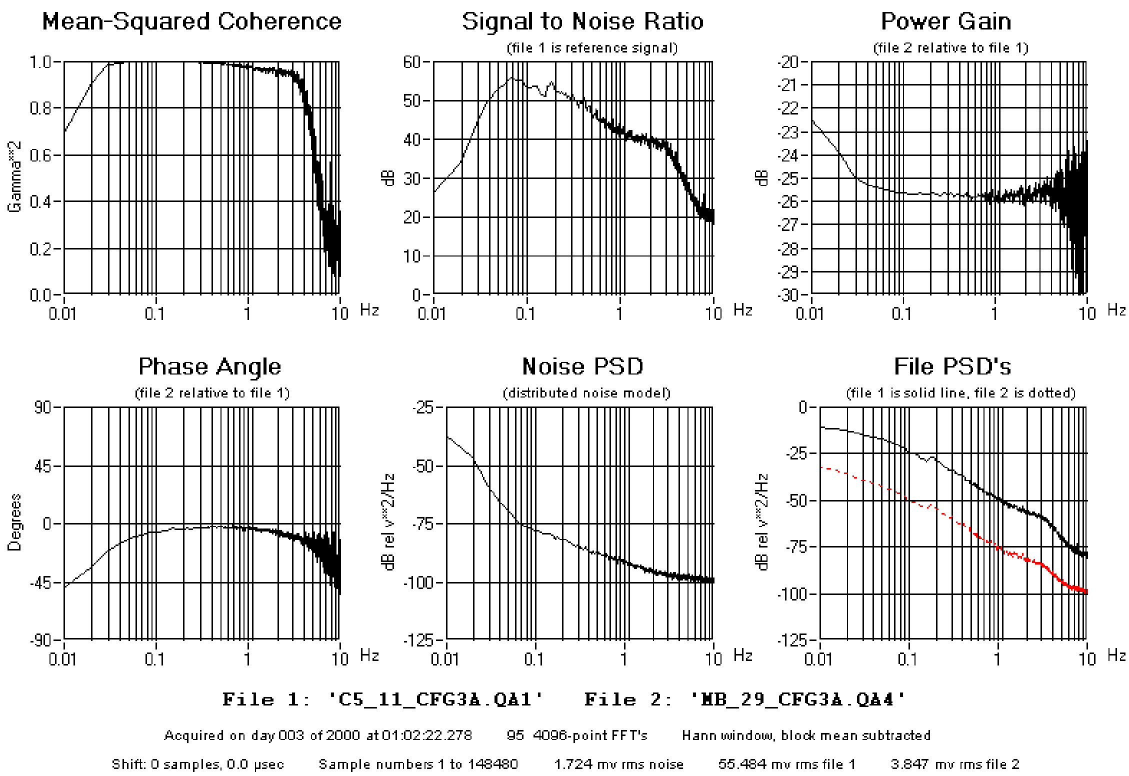

Figure 12 – Coherence Analysis Results Between Chaparral 5 and MB2000 Sensors

CONCLUSIONS AND RECOMMENDATIONS

The Chaparral Physics Model 5 is an improved version of the Chaparral 4. It met all IMS requirements tested. A response model was developed for the Chaparral 5 sensors used at IS-59, Hawaii. Sensitivity to temperature/wind was observed in the Chaparral 5. An installation technique to minimize these temperature effects was demonstrated at the Sandia FACT site. A technique to laboratory/field calibrate infrasonic sensors using a reference sensor was demonstrated using both the MB2000 and Chaparral 5 sensors. Techniques developed for sensor testing can be used for determining sensor conformance to IMS requirements.

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